A theoretical investigation of the optical gain in waveguide based on a silica matrix containing silicon nanograins and doped either with Nd3+ or with Er3+ ions

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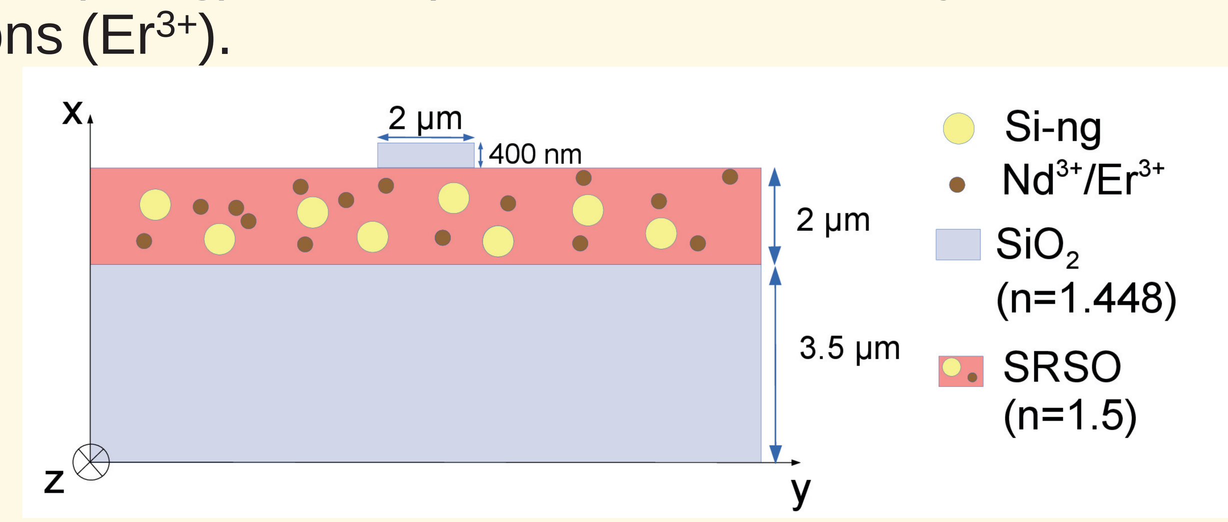
Introduction

Goal: Compare the optical gain in a waveguide containing silicon nanograins (Si-ng) and doped with either neodymium ions (Nd^{3+}) or erbium ions (Er^{3+}).



Transverse section view of the waveguide. Propagation of the pump and signal along z direction inside Silicon Rich Silicon Oxide (SRSO) layer.

New ADE-FDTD algorithm

Classic ADE-FDTD algorithm: Electric field **E**, magnetic field **H**, polarisations $\mathbf{P}_{ij}$ and populations $\mathbf{N}_i$ are calculated with a unique Δt imposed by the FDTD method. (In visible spectral range Δt ≈ 10^{-17} s).

➡ 10^6 years of calculation to reach steady state of $\mathbf{N}_i$ on a such waveguide**.**

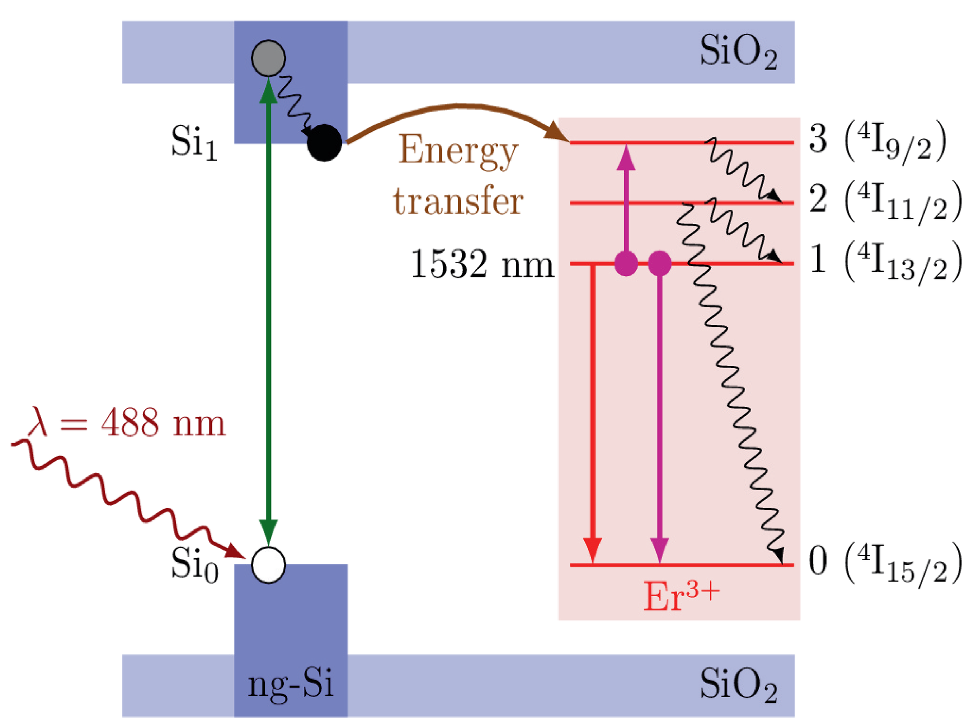
New ADE-FDTD algorithm[1]: separate loops for **E**, **H** and **P** on the one hand and populations $\mathbf{N}_i$ on the other hand.

➡ 7 days of calculation to reach steady state of $\mathbf{N}_i$**.**

(1) A. Fafin *et al*, "Modeling of the electromagnetic field and level populations in a waveguide amplifier: a multi-scale time problem," Opt. Express **21**, 24171-24184 (2013).

Rare earth excitation

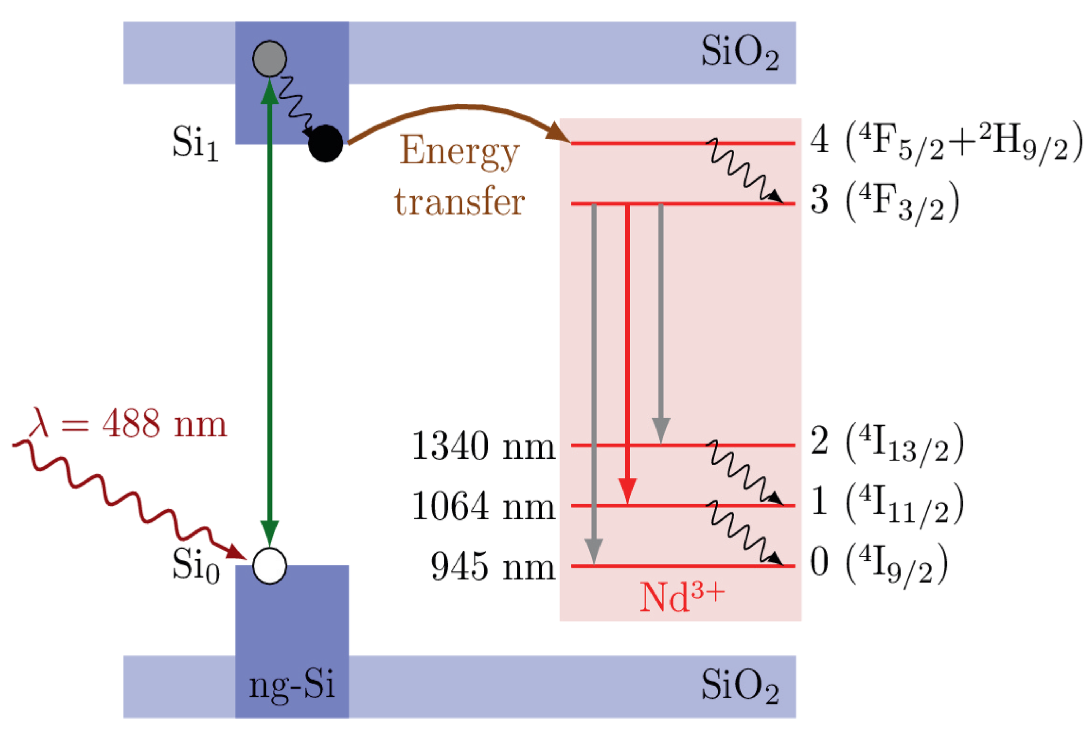
Erbium excitation mechanisms



- Modeling rare earth ions (Nd^{3+} or Er^{3+}) and silicon nanograins (si-ng) by a system of levels populations $\mathbf{N}_i$.
- Excitation of Nd^{3+} or Er^{3+} through the Si-ng by energy transfer.
- Si-ng are excited by a pump at 488 nm.
- : Non radiative transition
- : Radiative transition
- : Up-conversion

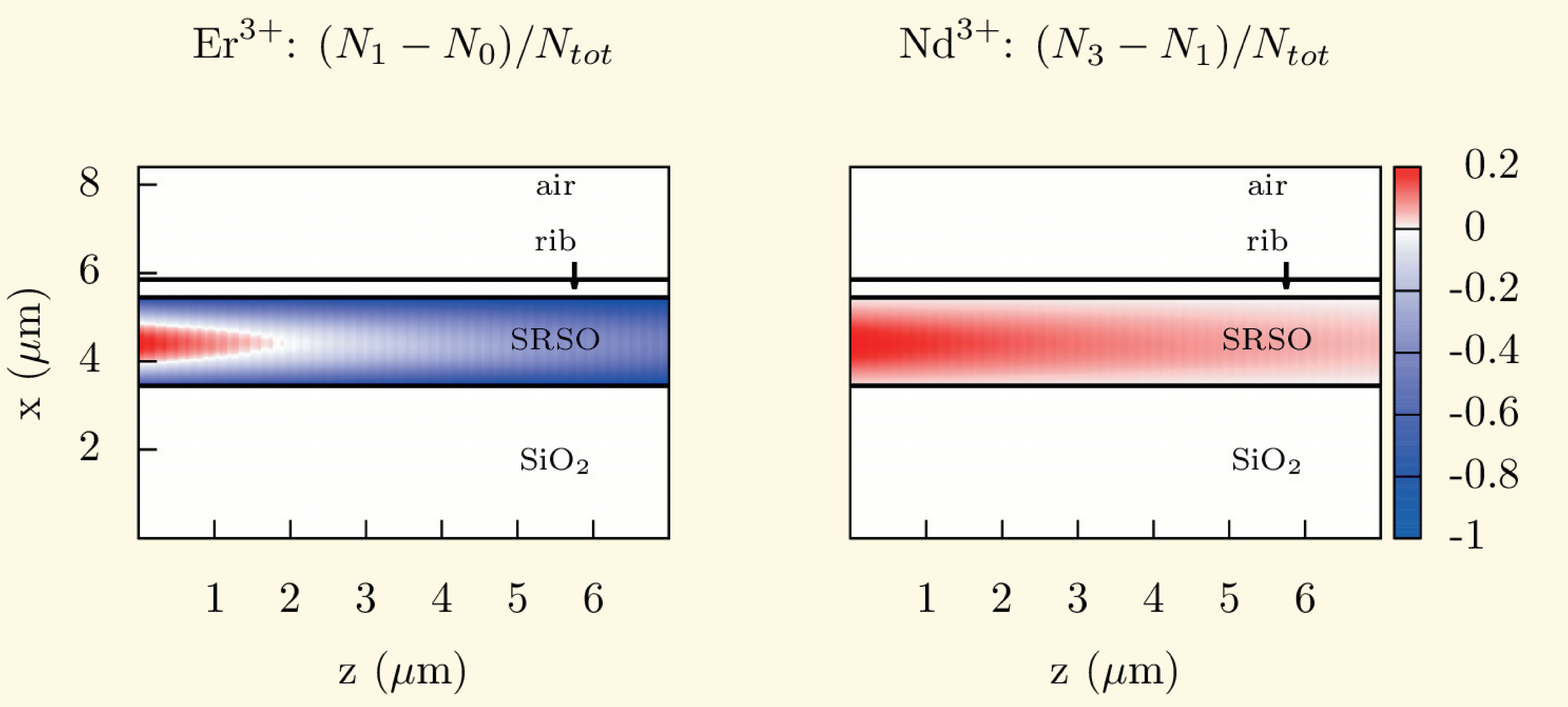
Erbium ions	Neodymium ions
Signal at 1532 nm : ➡ Transition between N1 and N0	Signal at 1064 nm : ➡ Transition between N3 and N1

Neodymium excitation mechanisms



Relative population difference

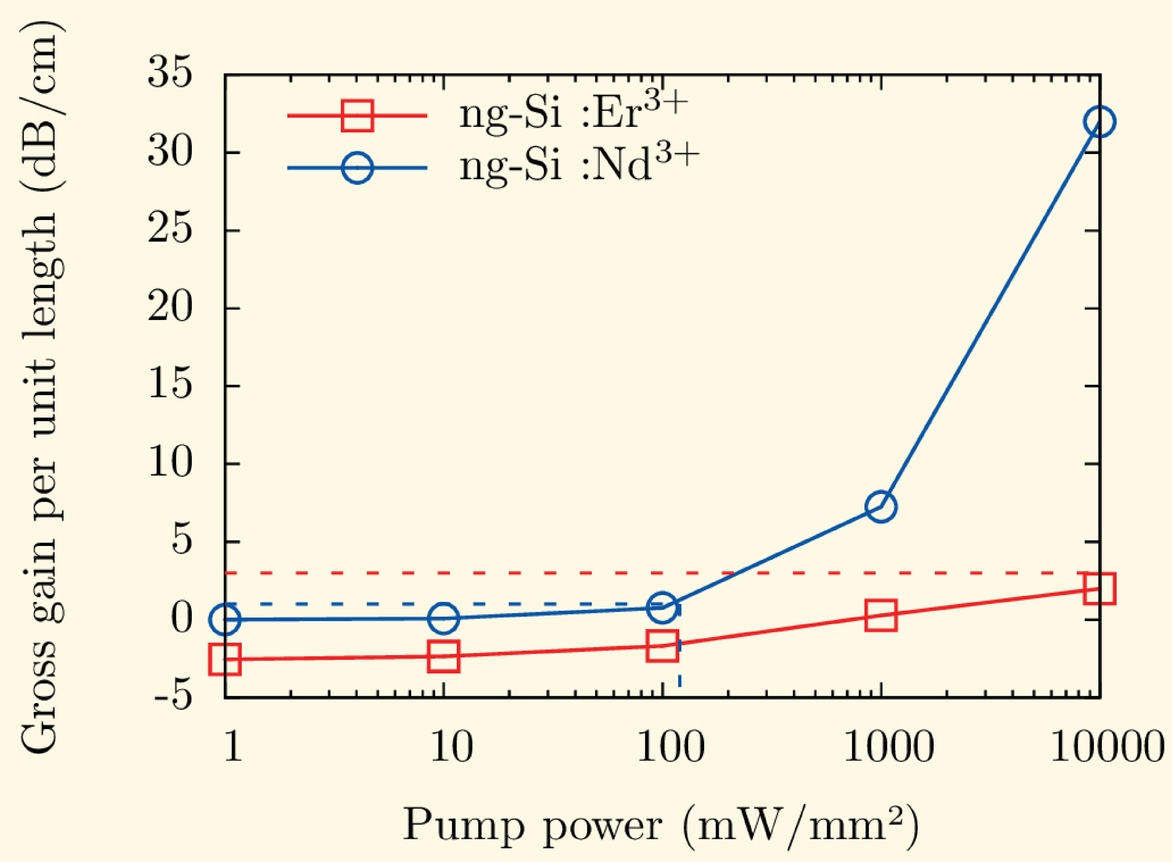
For a pump power of 1000 mW/mm²



Relative population difference reach population inversion only over a length of 1.5 µm. ➡ Er^{3+} is a 3-level system	Relative population difference reach population inversion along the whole structure. ➡ Nd^{3+} is a 4-level system

Gain

At the beginning of the waveguide (z=0)



Levels populations in steady states allow to calculate the gross gain. Experimental background losses are represented in dashed line (see Appl. Phys. Letter 99, 231114, 2011 for Er^{3+} and J. Appl. Phys. 114, 014906, 2013 for Nd^{3+}). **No positive net gain with Er^{3+}. Positive net gain with Nd^{3+} for a pump power higher than 120 mW/mm².**

Acknowledgment

The authors thank the French Nation Research Agency, which supported this work through the Nanoscience and Nanotechnology program (DAPHNES project ANR-08-NANO-005)

Conclusion

Using an original ADE-FDTD method we reach steady state of fields and populations in SRSO waveguide doped with either Nd^{3+} or Er^{3+} ions. A positive optical gain is reached only with Nd^{3+} ions. For a pump power of 10^5 mW/mm² the optical gain is over 30 dB/cm. For more details see Opt. Express **22**, 12296 (2014).

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